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Monitoring fatigue damage in materials using magnetic measurement techniques

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Measurements of hysteresis and Barkhausen effect (BE) have been made on 0.1 wt % C Fe–C alloys subjected to strain-controlled fatigue at various strain amplitudes. A relationship between the fatigue lifetime and strain amplitude was observed. The hysteresis properties of the samples cycled at different strain amplitudes were found to vary systematically with expended fatigue life. These properties showed significant changes in the initial and final stages of fatigue, while between these stages they remained stabilized. In the stable stage the remanence was found to decrease, whereas the coercivity increased with increasing strain amplitude. Variations in BE signal during fatigue were found to be closely related to the microstructural changes observed on the sample surface. These results are interpreted in the context of the changes in microstructure caused by fatigue damage, and the effects of the formation and propagation of fatigue cracks on the field distribution and domain structure in the vicinity of the cracks. © *1999 American Institute of Physics.* [S0021-8979(99)41908-5]

I. INTRODUCTION

Fatigue accounts for most of the service failures encountered in industry.[1] Therefore, it is important to develop techniques to monitor fatigue damage and fatigue lifetime of industrial components nondestructively. Magnetic measurement techniques can be used for this purpose, as the magnetic properties of ferromagnetic materials are sensitive to the microstructural changes caused by fatigue damage.[2] Investigations have been made on the variations of magnetic properties with fatigue damage[3,4] and the effects of cyclic stress on magnetic hysteresis properties.[5,6] Previous studies have also shown that fatigue lifetime is related to the prefatigue magnetic properties[7] and the Barkhausen effect (BE) signal measured in the early stages of fatigue.[8]

In the case of strain-controlled fatigue the fatigue properties, such as fatigue lifetime, are strongly dependent on the strain amplitude.[1] The objective of this study is to investigate the variations in magnetic properties with the microstructural changes during fatigue under strain-controlled conditions, and the effects of varying strain amplitude on the fatigue and magnetic properties.

II. EXPERIMENTAL DETAILS

Fe–C alloy bars with 0.1 wt % C were austenitized at 905 °C for 2 h and then furnace cooled at a rate of 2 °C/min. The heat treated samples were found to have a ferrite/pearlite structure with a volume fraction of pearlite of 9.4% and a mean ferrite grain size of 29 μm. The samples were machined to an ''hour glass'' shape with a minimum diameter of 6.35 mm at the center. They were then carefully ground and electro-polished to obtain a smooth surface finish.

Strain-controlled fatigue tests were performed using a servo-hydraulic mechanical testing machine. During a test the sample was cyclic-strained at a frequency of 2 Hz with a fixed strain amplitude ϵ. Various values of ϵ ranging from 0.1% to 1.1% were used. The test was halted at predetermined intervals under the zero strain condition. *In situ* measurements of hysteresis and BE signal were made using surface sensors. Detailed description of the equipment used and the experimental procedures has been given in previous publications.[9,10] Surface replicas were prepared and examined by scanning electron microscopy (SEM) in order to study the changes in surface microstructure during fatigue.

III. RESULTS

Figure 1 shows the variations in the magnetic hysteresis properties with fatigue cycle for $\epsilon = 0.1\%$. It was found that

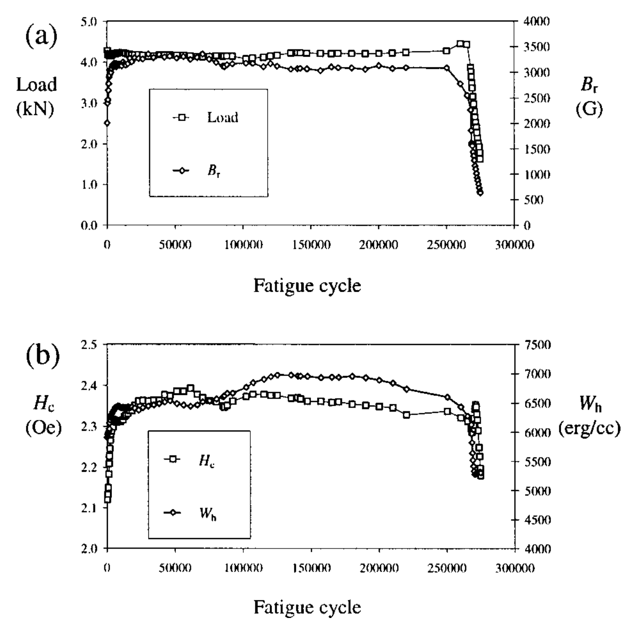

FIG. 1. Plots of (a) load and remanence B_r, (b) coercivity H_c, and hysteresis loss W_h as functions of fatigue cycle for the sample cycled at $\epsilon = 0.1\%$.

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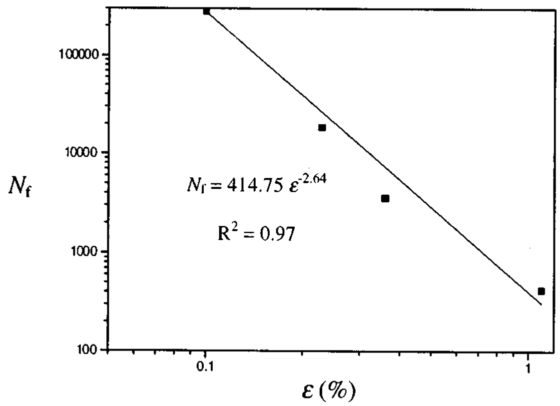

FIG. 2. Plot of the fatigue lifetime N_f (number of fatigue cycles to failure) as a function of ϵ in logarithmic scale.

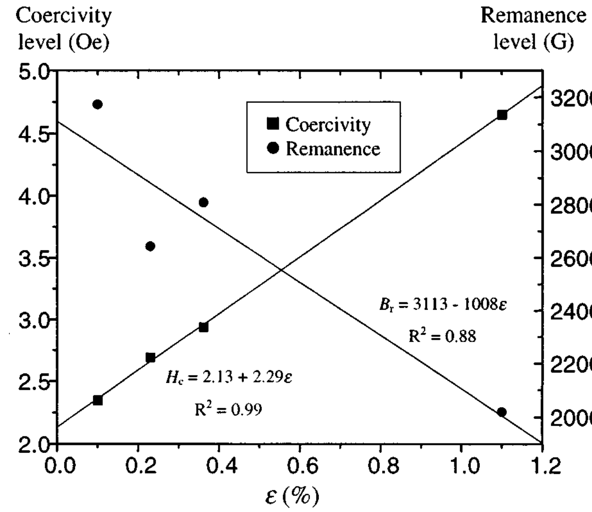

FIG. 4. Plots of the stable coercivity and remanence levels measured in the second stage of fatigue as functions of ϵ.

the coercivity H_c, remanence B_r, and hysteresis loss W_h first increased, and then remained approximately stable until 250 000 cycles. After that these properties decreased dramatically until the sample fractured. A similar trend was observed in the load amplitude required to obtain the predetermined strain level.

As Fig. 2 shows, the samples fatigued at high strain amplitudes ($\epsilon > 0.1\%$) exhibited low-cycle fatigue behavior (i.e., failures occurred after less than 10^5 cycles). It was found that the fatigue lifetime N_f (number of cycles to failure) of the samples are consistent with those of low-carbon steels fatigued at the same strain levels.[11] In the present study N_f was found to be related to ϵ by the empirical relation $N_f = 414.75\epsilon^{-2.64}$. This relation is similar in form to the Coffin–Manson equation which states that the fatigue lifetime is related to the plastic strain amplitude.[1] A general trend was observed in the evolution of the magnetic properties of the samples fatigued at different ϵ. An example is shown in Fig. 3, in which B_r is plotted against % fatigue life for different ϵ. The root-mean-square (rms) values of the BE signal V_{BE} measured from the sample cycled at $\epsilon = 1.1\%$ are also shown. These results suggest that the fatigue life of the samples can be divided into three stages according to the variations in magnetic properties caused by fatigue. In stage I (0%–5% of fatigue life) B_r increased for small ϵ, while for $\epsilon = 1.1\%$ B_r decreased with increasing % fatigue life. In stage II (5%–90%) B_r remained stable, whereas V_{BE} decreased gradually. In stage III (the last 10%–25% of fatigue life) B_r decreased drastically but V_{BE} showed a significant increase.

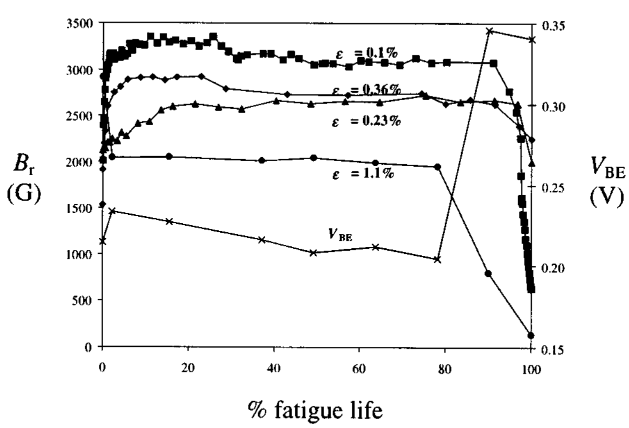

FIG. 3. Plot of remanence B_r as a function of % fatigue life for different values of ϵ. The rms values of BE signal V_{BE} measured from the sample cycled at $\epsilon = 1.1\%$ are also shown.

The levels at which H_c and B_r became stable in stage II were found to depend on ϵ. The stable coercivity and remanence levels were calculated by averaging the measured values of H_c and B_r, respectively, over this stage, and were plotted as functions of ϵ in Fig. 4. It was found by empirical curve fitting that the stable coercivity level increases linearly, while the stable remanence level decreases linearly with increasing ϵ. Nevertheless the stable remanence level shows a larger scatter and hence, a weaker correlation with ϵ than the stable coercivity level. The present results therefore indicate that it is possible to estimate the strain amplitude and hence, the fatigue lifetime (Fig. 2) of a sample by measuring H_c during fatigue.

Figure 5 shows the SEM micrographs of the surface replicas taken from the sample fatigued at $\epsilon = 0.1\%$. In stage I no microstructural change was found. Formation of slip bands was observed at the beginning of stage II [Fig. 5(a)], and the amount of slip bands was found to increase throughout this stage [Fig. 5(b)]. This resulted in extensive surface damage [Fig. 5(c)], and eventually led to the nucleation of fatigue cracks. Propagation of a macroscopic fatigue crack was observed in stage III [Fig. 5(d)]. This was accompanied by the dramatic reduction in the load amplitude and the magnetic properties.

IV. DISCUSSION

In the present study the microstructural changes observed in different stages of fatigue were found to be consistent with the high-strain fatigue behavior of steel reported in the literature.[12] The variations in the magnetic properties with % fatigue life can be interpreted in terms of these microstructural changes. In the early stage of fatigue the increase in coercivity and hysteresis loss is probably caused by

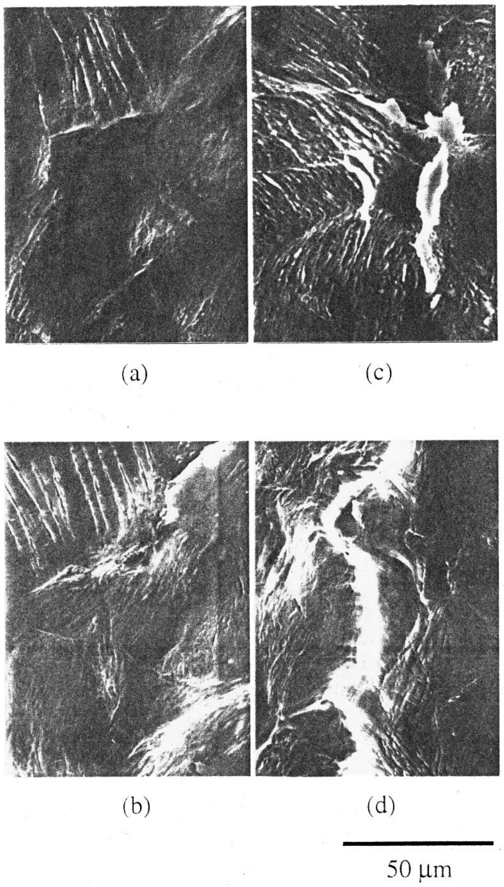

FIG. 5. SEM micrographs of the surface replicas taken at (a) 5%, (b) 20%, (c) 75%, and (d) 94% of fatigue life from the sample cycled at $\epsilon = 0.1\%$.

fatigue hardening, during which the dislocation density inside the material increased rapidly. This resulted in stronger domain wall pinning, causing H_c and W_h to increase. Upon further cycling the dislocations rearranged into cellular structures. The magnetic hysteresis properties then became dependent on the dislocation cell size as the cell boundaries provide strong pinning sites for domain walls. In the second stage of fatigue the dislocation cell structure became stabilized. This is manifested in the stabilization of the load amplitude. In this stage the magnetic hysteresis properties remained unchanged.

It has been shown that the size of dislocation cells in annealed iron subjected to strain-controlled fatigue decreases with strain amplitude.[13] Therefore, it is expected that in stage II H_c should become stabilized at a higher level for larger ϵ because of the stronger domain wall pinning caused by the smaller dislocation cells. Such a relationship between the stable coercivity level and ϵ was found in the present study. In the final stage of fatigue the growth of a macroscopic fatigue crack produced strong demagnetizing effects and flux leakage at the crack, making it more difficult to magnetize the sample to saturation. As a result, the magnetic hysteresis properties decreased.

The variations in V_{BE} during fatigue were found to be closely related to the changes in surface microstructure. In stage II the formation of slip bands, which are pinning sites for domain walls, hindered the domain wall motion in the surface layer. As the amount of slip band increased with fatigue cycling, the domain wall jumps became smaller, resulting in weaker BE signals. The increase in V_{BE} in the final stage of fatigue could be caused by the propagation of fatigue cracks. As the cracks grew into the sample more closure domains formed at the surface of discontinuity. This increased the total area of domain walls and hence, the number of BE jumps, giving rise to a larger V_{BE}.

V. CONCLUSIONS

A study of the variations in magnetic properties has been made on Fe-0.1% C alloys subjected to strain-controlled fatigue at various strain amplitudes. A general trend was observed in the variations in the magnetic hysteresis properties with % fatigue life. Variations in V_{BE} were found to be closely related to the changes of surface microstructure. The stable remanence level measured in the second stage of fatigue decreased, while the stable coercivity level increased with strain amplitude. This relationship makes magnetic measurement promising techniques for monitoring the strain amplitude and hence the fatigue lifetime of materials.

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[1] G. E. Dieter, *Mechanical Metallurgy* (McGraw-Hill, London, 1988).
[2] D. C. Jiles, NDT & E Int. **21**, 311 (1988).
[3] M. S. C. Bose, NDT & E Int. **19**, 83 (1986).
[4] M. B. Shah and M. S. C. Bose, Phys. Status Solidi A **86**, 275 (1984).
[5] M. K. Devine, D. C. Jiles, and S. Hariharan, J. Magn. Magn. Mater. **104**, 377 (1992).
[6] Z. J. Chen, D. C. Jiles, and J. Kameda, J. Appl. Phys. **75**, 6975 (1994).
[7] Y. Bi, M. R. Govindaraju, and D. C. Jiles, IEEE Trans. Magn. **32**, 3928 (1997).
[8] G. Donzella and S. Granzotto, J. Magn. Magn. Mater. **133**, 613 (1994).
[9] D. C. Jiles, A. R. Eichmann, and M. K. Devine, J. Appl. Phys. **73**, 5617 (1993).
[10] A. P. Parakka and D. C. Jiles, J. Magn. Magn. Mater. **140–144**, 1841 (1995).
[11] R. W. Landgraf, *Fatigue and Microstructure* (American Society for Metals, Ohio, 1979), p. 443.
[12] C. Laird, *Fatigue and Microstructure* (American Society for Metals, Ohio, 1979), p. 168.
[13] H. Abel-Raouf, P. P. Benham, and A. Plumtree, Can. Metall. Q. **10**, 87 (1971).